Performance of Duplex Communication Between a LEO Satellite and Terrestrial Location Using a GEO Constellation

Daryl C. Robinson*, Vijay K. Konangi*, and Thomas M. Wallett**
*Department of Electrical and Computer Engineering
Cleveland State University
Cleveland, Ohio 44115

** Satellite Networks and Architectures Branch
NASA Glenn Research Center
Cleveland, Ohio 44135

ABSTRACT

A network comprised of a terrestrial site, a constellation of three GEO satellites and a LEO satellite is modeled and simulated. Continuous communication between the terrestrial site and the LEO satellite is facilitated by the GEO satellites. The LEO satellite has the orbital characteristics of the International Space Station. Communication in the network is based on TCP/IP over ATM, with the ABR service category providing the QoS, at OC-3 data rate. The OSPF protocol is used for routing. We simulate FTP file transfers, with the terrestrial site serving as the client and the LEO satellite being the server. The performance characteristics are presented.

INTRODUCTION

The International Space Station (ISS) is a LEO (low earth orbit) satellite which needs continuous communication with a terrestrial location so that services such as communications, tracking, telemetry and data acquisition can be provided. An extensive worldwide network of tracking and communication ground stations could provide this type of service. Since each ground station can communicate for very brief periods of time when the ISS is in line of sight, an elaborate terrestrial network of ground stations is necessary for global coverage [1]. The cost of maintaining, operating and upgrading this worldwide network is prohibitive.

An alternate approach to facilitate communication between the terrestrial location and the ISS is to use a constellation of GEO (geosynchronous earth orbit) satellites. The Tracking and Data Relay Satellite System (TDRSS) used by NASA represents such a system [2]. The TDRSS consists of three GEO satellites and a ground terminal facility located at White Sands, New Mexico. The system can transmit and receive data, and track a LEO user spacecraft for 100 percent of its orbit.

In this paper, we consider a constellation of three GEO satellites, with orbital characteristics similar to the TDRSS satellites, which can provide 100 percent global coverage. Unlike the TDRSS satellites, which are bent-pipe systems, the GEO satellites in this paper function as routers in a network. Our GEO satellites are also assumed to have inter-satellite links. A LEO satellite, such as the ISS, can communicate with the White Sands Ground Terminal (WSGT) via the GEO constellation [3]. Our objective in this paper is to determine the performance characteristics for communication between the ISS and the WSGT, using the GEO constellation. The communication is based on TCP/IP over ATM at OC-3. We present a comprehensive set of simulated performance characteristics -- throughput, end-to-end delay and server utilization -- for a range of FTP file sizes.

SATELLITE NETWORK

The network consists of a ground terminal at the White Sands Ground Terminal (WSGT), White Sands, New Mexico; three GEO satellites which provide worldwide coverage and the International Space Station in a LEO orbit. The WSGT is responsible for the command, telemetry, tracking, and control of the GEO constellation and the ISS. The three GEO satellites, GEO-1, GEO-2 and GEO-3 are positioned over the Equator at 41° West, 275° West and 174.3° West longitude, respectively. These satellites are at an altitude of 22,300 statute miles (35,888 kilometers) and orbit geosynchronously. The GEO-1 satellite is in direct line-of-sight communication with WSGT. The simulation of the ISS, which is a LEO satellite, is based on the following orbital characteristics: semi-major axis = 6734.32 km, eccentricity = 0.0014064, inclination = 51.66°, right ascension of the ascending node = 243.89°, mean anomaly = 222.30° and argument of perigee = 137.91°. The network is illustrated in Figure 1

.

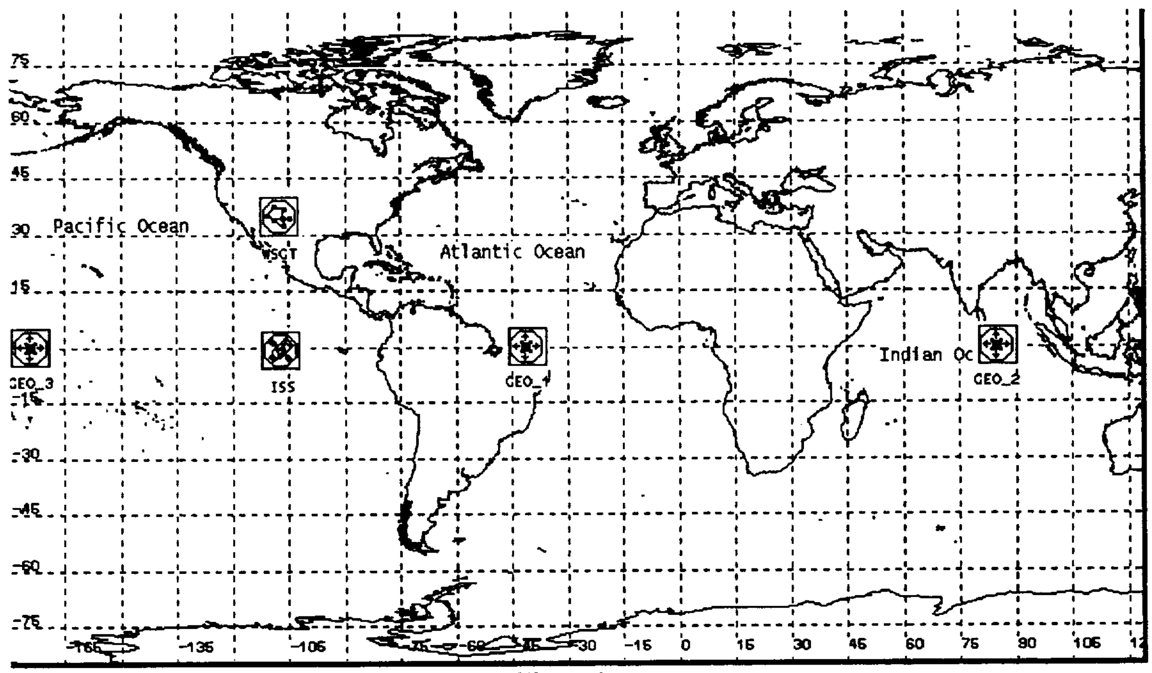


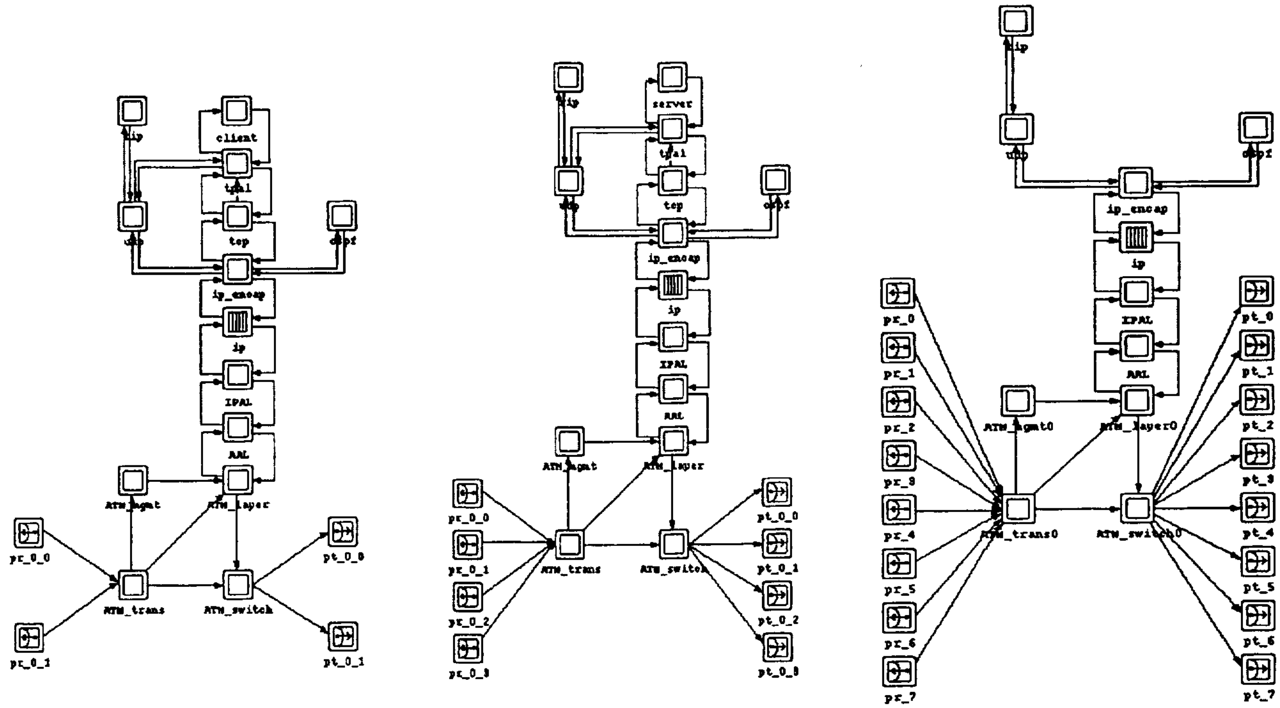
Figure 1

The ISS communicates with the WSGT through the GEO satellites. The topology is such that the WSGT communicates solely with GEO-1. The GEO-2 and GEO-3 satellites can communicate directly with GEO-1, but not with each other. The ISS communicates with the closest GEO satellite. All communication in the network between the ISS, the GEO satellites, and the WSGT is at OC-3 (155 Mbps).

NODE ARCHITECTURES

The node architectures of the terrestrial client, GEO router and the LEO server are depicted in Figure 2.

The WSGT and the LEO satellite communicate using a client-server paradigm of interaction. The LEO server application waits passively for contact, while the client initiates communication actively. The node architecture of the terrestrial site consists of the application-level FTP client using TCP/IP over ATM. The ATM layer uses the ABR (Available Bit Rate) service category. The OSPF (Open Shortest Path First) protocol is used for routing. The node architecture of the LEO is complementary to the terrestrial client, and has the application-level server. The three GEO satellites function as routers and their node architectures are comprised of IP over ATM, with OSPF being again used for routing.



Terrestrial client LEO server GEO router

Figure 2

TCP/IP OVER ATM

The TCP layer implements connection-oriented, reliable, byte stream transport using the potentially unreliable datagram service provided by the IP layer [4]. TCP is used to establish and terminate connections using three-way handshake protocols. Sliding window based flow control is used to prevent the transmitter from overwhelming the receiver with data. Reliability on an end-to-end basis is achieved by using acknowledgements. The retransmission time-out (RTO) is dynamically varied using Jacobson's algorithm. To avoid the retransmission ambiguity problem, Karn's algorithm is used. For congestion avoidance and control, the slow-start algorithm is used. The silly window syndrome is avoided using Nagle's algorithm.

The IP layer is a connection-less network protocol which enables the integration of heterogeneous networks. It provides an unreliable datagram service. Routing across multiple networks is the responsibility of the IP layer. The IP layer allows data to be interpreted consistently as they traverse the network.

The ATM is a streamlined protocol with minimal error and flow control features, which reduces the number of overhead bits for each cell and therefore the overhead involved in the processing of each cell [5]. This combined with the fixed-size cells of ATM enables it to operate at high data rates. The ATM layer provides connection-oriented, in-sequence, unreliable, and guaranteed quality-of-service cell transport. The ABR service category of ATM is intended for bursty traffic sources whose bandwidth range is known approximately. An application using ABR specifies the minimum cell rate (MCR) required and the peak cell rate (PCR) at which it will transmit cells. The network then allocates resources to ensure that all ABR applications receive at least their MCR capacity. ABR is the only service category in which the network provides explicit feedback to the sources, asking them to reduce the transmission rate in the presence of congestion and thus enabling the fair allocation of resources.

RESULTS

To investigate the performance of TCP/IP over ATM using ABR in a constellation of GEO satellites, we simulated file transfers using FTP. The requests for transfers are generated by the client at WSGT using a Poisson distribution with a mean of 5 requests per hour. Each request results in one TCP session, which transfers the file from the server on the ISS to the client. The average size of the files is modeled using a normal distribution. Results are presented for a range of means: 60 KB, 300 KB and 1500 KB. The simulation results are for one-half day (43,200 seconds) of operation of the satellite network for the indicated file sizes. Since the orbital period of the ISS is 91.66 minutes, these simulations will involve at least 7.86 orbits.

In our simulations, we monitored the number of FTP requests submitted to the transport layer by the application layer of the client, and the corresponding number of FTP responses received by the application layer of the client. As both plots are nearly identical, Figure 3, we conclude that although the ISS is circumnavigating the earth in its orbit, the satellite network is functioning so as to allow continuous communication from the ISS to the terrestrial client even if there is no line-of-sight communication.

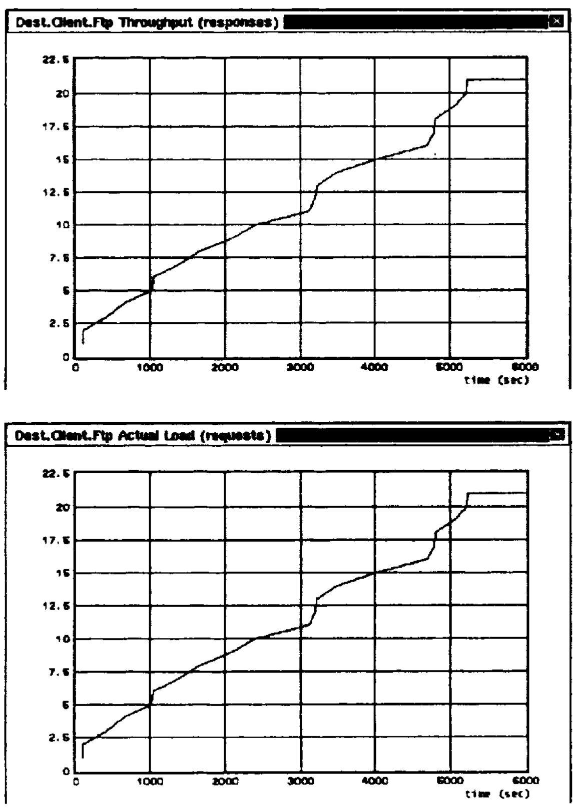


Figure 3

The conformity of the plots indicates that for every request sent by the client, a response follows shortly thereafter. This simulation is for 6,000 seconds, which is adequate time to simulate a single LEO orbit of 5,499.6 seconds. Additionally, we examined the end-to-end (ETE) delay, which is the time from the transmission of a request from the FTP application in the client to the time a response packet is received by the client. For this test we used a high mean file transfer rate of 10 files per hour and a small mean file size of 5 KB. The ETE delays were of the order of 200 ms, approximately the round-trip time delay in transmitting a message and receiving a response from a geosynchronous satellite. Figure 4 is a plot of the ETE delays in the scenario just described, for one-half day of operation (43,200 seconds).

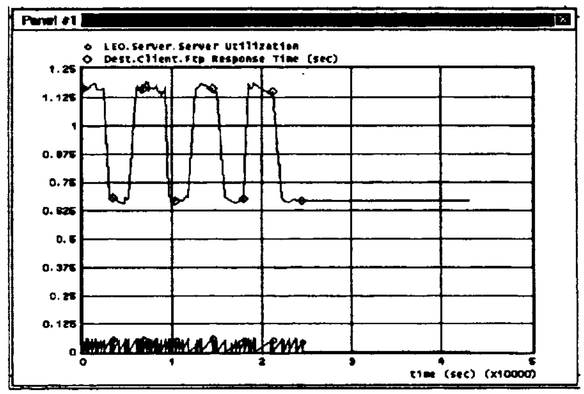


Figure 4

The fact that the server was utilized only for about 25,000 seconds was determined by the number of file transfers, which is a random variable, and the file sizes, which is also a random variable. The plot of end-to-end delay is oscillatory in accordance with the fact that the elliptical orbit of the ISS is also oscillatory. Points on the curve which are minima correspond to those times in the simulation when the ISS is closest to the GEO-1 satellite which communicates directly with the client. After the server stops transferring files at approximately 25,000 seconds, for the remainder of the simulation, the end-to-end delay is determined by the rate at which the client processes the accumulated files in its queue and hence the essentially constant nature of the delay. Any deviation from a constant end-to-end delay is not due to the randomly chosen file transfer sizes, which are centered about the mean; but it is due to the propagation delay through space.

The throughput represents the average number of bits successfully received or transmitted by the receiver or transmitter channel, as the case may be, per unit time in bits per second. At various points in time, the throughput is essentially the running average from the start of the simulation up to that point. The throughput for the communication path consisting of the LEO server, GEO-3 satellite, GEO-1 satellite and the terrestrial client at WSGT is shown in Figure 5. In Figure 5(a), the throughput shown is for communication between the transmitter on the LEO server and the receiver on the terrestrial client for 60 KB files. This throughput is determined by the frequency of the requests for file transfers, the average size of each file and the data rate of the channel. As expected, the throughputs of the LEO transmitter and client receiver are almost identical, and the client receiver throughput is offset from the LEO transmitter throughput due to the propagation delay. Also, the client receiver throughput is slightly more than the transmitter throughput because the client receives duplicate packets from the GEO-2 satellite. In Figure 5(a), the sharp increases in throughput correspond to those periods when the LEO is in direct line-of-sight communication with GEO-3 and the server on the LEO is transferring a file to the terrestrial client. The throughput in the forward direction, i.e., from the client transmitter to the LEO receiver via GEO-1 satellite and GEO-3 satellite is shown in Figure 5(b). The LEO receiver has a higher throughput since it receives duplicate packets from the GEO-2 satellite.

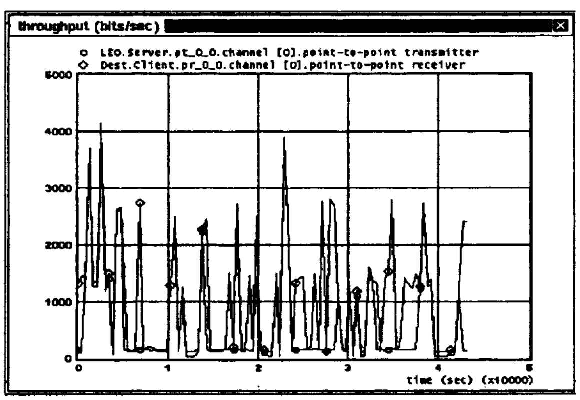


Figure 5(a)

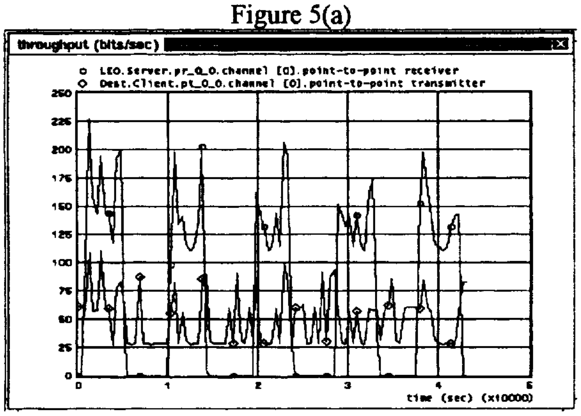


Figure 5(b)

Figure 5 – 60 KB Files

A similar set of results for 300 KB files is shown in Figure 6.

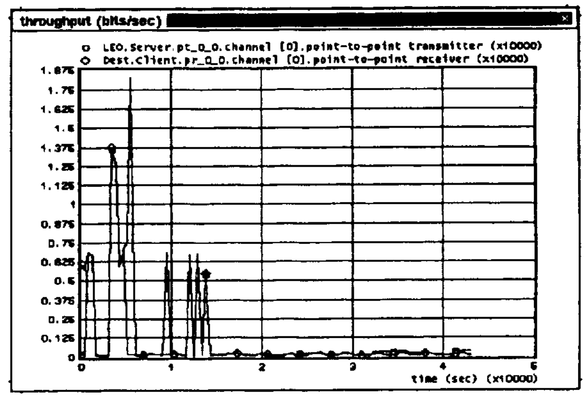


Figure 6(a)

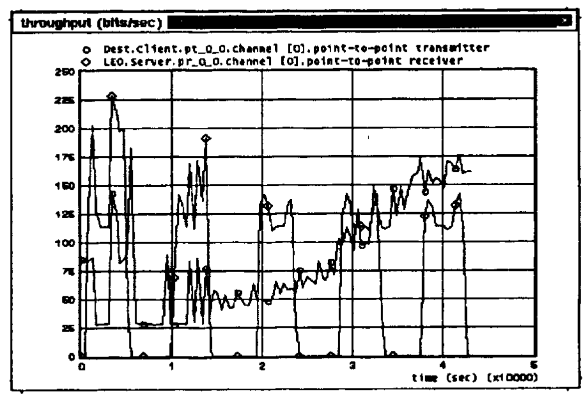


Figure 6(b)

Figure 6 – 300 KB Files

The FTP response time, which is the end-to-end delay measured from the initiation of a request from the FTP application in the client to the completion of the file transfer, is shown in Figure 7 for 60 KB file transfers. There are two reasons for the periodic variation of this statistic. First, the round-trip propagation delay from the terrestrial client to the LEO server depends on the orbit of the LEO satellite and its position relative the satellites in the GEO constellation. This delay has a periodic behavior. Second, the end-to-end delay is dependent upon the queueing and processing delays at the server. This is a function of the file size and the frequency of the file transfers. The FTP response time for 60 KB files varies from 3 seconds to 6 seconds. Since the throughput for 60 KB files is low in comparison to the data rate of the channel (Figure 5), the large end-to-end delay is due to the slow server, i.e., the processing and queueing delays in the server.

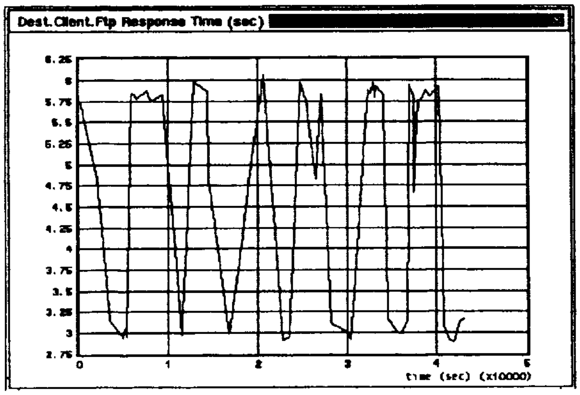


Figure 7

Figures 8 and 9 show the FTP response time for 300 KB and 1.5 MB files, respectively. As the file transfer size increases, the queueing and processing delays in the server lead to excessive end-to-end delays.

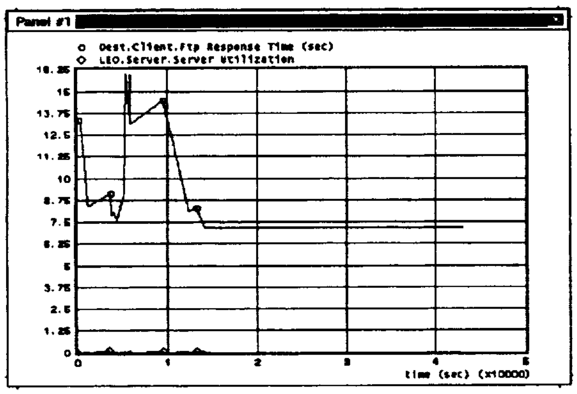


Figure 8

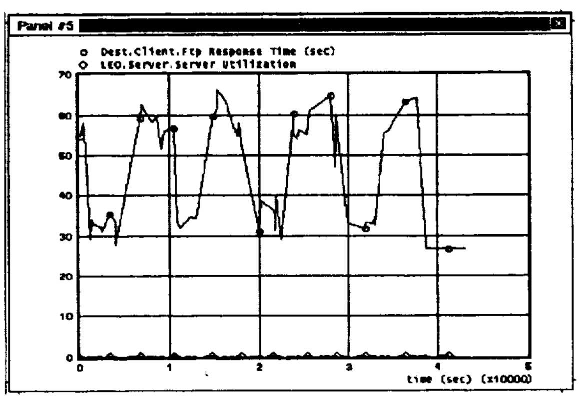


Figure 9

CONCLUSIONS

In this paper a network comprised of a terrestrial site, a constellation of three GEO satellites, and a LEO satellite with orbital characteristics of the International Space Station was modeled and simulated. The communication in the network is based on TCP/IP over ATM with the ABR service category providing the QoS. The OSPF protocol was used for routing. We simulated FTP file transfers, with the terrestrial site serving as the client and the LEO satellite being the server. A comprehensive set of performance characteristics – throughput, end-to-end delay and server utilization – for a range of FTP file sizes were presented. When the file sizes increase, the end-to-end delays are quite large; this is due to the processing delay in the server. Since the orbital characteristics of the US Space Shuttle are similar to that of the International Space Station, we expect similar performance characteristics.

ACKNOWLEDGEMENT

The authors thank Dr. Kul B. Bhasin and the Satellite Networks and Architectures Branch of the NASA Glenn Research Center for the support of this research.

REFERENCES

[1] V.K. Konangi, T.M. Wallett, and K.B. Bhasin, "Modeling and Analysis of a Satellite-Terrestrial Hybrid Network," Proceedings of Sixth International Conference on Telecommunication Systems, Modeling and Analysis, 1998, pp. 427-432.

[2] http://www530.gsfc.nasa.gov/tdrss/oview.html

[3] C-K. Toh and V.O.K. Li, "Satellite ATM Network Architectures: An Overview," IEEE Network, September/October 1998, pp. 61-71.

[4] W. R. Stevens, TCP/IP Illustrated, Vol. 1: The Protocols, Reading, MA: Addison-Wesley, 1994.

[5] W. Stallings, High-Speed Networks: TCP/IP and ATM Design Principles, Upper Saddle River, NJ: Prentice Hall, 1998.

TECHNICAL PUBLICATION APPROVAL FORM

AUTHOR(S) (*Continue in Remarks.*)	ORG. CODE	AFFILIATION (*See page 2.*)	PHONE NO.	MAIL STOP	ROOM NO.
DARYL C. ROBINSON		G	216-433-6325	54-5	34
VIJAYA K. KONANGI		G	216-433-3673	54-5	207
THOMAS M. WALLETT		GRC	216-433-3673	54-5	207

Funding Division No. 5600 Current Funded Task No. V9T2005 Funding RTOP No. 632-50-5A-00

Lewis Contract Monitor ____ Org. Code ____ Phone No. ____ Mail Stop ____ Room No. ____

Contract or Grant No. NCC3-595 Other Report No. ____ Non-NASA Funding (*Specify*) ____

Contract Organization and Complete Address ____

(1) REPORT TITLE AND SUBTITLE

PERFORMANCE OF DUPLEX COMMUNICATION BETWEEN A LEO SATELLITE AND TERRESTRIAL LOCATION USING A GEO CONSTELLATION

(2) REPORT TYPE (See Page 2 and NPG 2200.2A)

- ☐ TP
- ☐ TM
- ☐ CR
- ☐ CP
- ☐ SP
- ☒ Presentation
- ☒ TM or CR
- ☐ No TM or CR (*including oral*)
- ☐ Journal article/book
- ☐ Informal STI (*Write URL in Remarks.*)

(3) WORK REQUESTED

- ☐ Edit
- ☐ Process
- ☒ Credit only

Attach complete report.

(4) MEETING TITLE, LOCATION, AND DATE
JOURNAL TITLE

INTERNATIONAL MOBILE SATELLITE CONFERENCE (IMSC '99) JUNE 16 – JUNE 18, 1999
OTTAWA, ONTARIO, CANADA

PUBLISHER/SPONSOR

CRC, JPL, NASA, CSA ASC

(5) DISTRIBUTION

☒ Standard ☐ Nonstandard ☐ Local

SECURITY CLASSIFICATION

☒ Unclassified ☐ Confidential ☐ Secret

Patent Notice given to authors: Initials ____ Date __/__/__

(6) DISTRIBUTION AVAILABILITY CATEGORY (See NGP 2200.2A)

No Restriction

- ☒ Publicly available
- ☐ Publicly available SBIR (*attach letter*)

Confidential Commercial

- ☐ Trade secret
  - ☐ Patent ☐ License Agreement
  - ☐ Space Act Agreement (SAA) No. ____
- ☐ Copyrighted
- ☐ SBIR Restricted until __/__/__

Export Controlled

- ☐ ITAR – USML Category No. ____
- ☐ EAR – ECCN ____
- ☐ LERD

Availability for restricted document

- ☐ U.S. Government Agencies and U.S. Government Agency Contractors Only
- ☐ NASA Contractors and U.S. Government Agencies Only
- ☐ U.S. Government Agencies Only
- ☐ NASA Personnel and NASA Contractors Only
- ☐ NASA Personnel
- ☐ Available Only with Approval of Issuing Office (Program Office or NASA Center)

Limited until __/__/__ (*if applicable*)

(7) TRADE NAMES USED? ☐ Yes ☒ No

(8) SUBJECT CATEGORY(IES)

(9) SUBJECT TERMS (*From NASA Thesaurus*)

GEO SATELLITE ATM

Approvals must be complete before your report can be processed.

(10) MANAGEMENT REVIEWS AND APPROVALS

	Initial	Date
Author/Technical Monitor name (*printed*): THOMAS M. WALLETT	TW	6/30/99
Branch Chief/Office Head name (*printed*): KUL BHASIN	KB	6/28/99
Division Chief name (*printed*): W Dan Williams	WDW	7/2/99

Editing waived? ☐ Yes ☐ No

TECHNICAL REVIEW COMMITTEE (*Required for standard distribution reports.*)

Chair or Reviewer name (*printed*) ____

Checker name (*printed*) ____

Advisor name (*printed*) ____

(11) DISTRIBUTION REVIEWS AND APPROVALS

	Signature	Date
Author/Originator name (*printed*): THOMAS WALLETT	Thomas Wallett	6/30/99
Branch Chief name (*printed*): KUL BHASIN	Kul Bhasin	6/28/99
Division Chief name (*printed*): W. Dan Williams	W Dan Williams	7/2/99
Intellectual Property Officer name (*printed*) (*if required*): Robert Jones	Robert Jones	7/2/99
Center Export Administrator name (*printed*): John Pouch	John Pouch	7/7/99

REMARKS E11893